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**EDGEWOOD ARSENAL
TECHNICAL REPORT**

EATR 4705

**IMPACTION EFFICIENCY OF CYLINDRICAL COLLECTORS
IN LAMINAR AND TURBULENT FLUID FLOW**

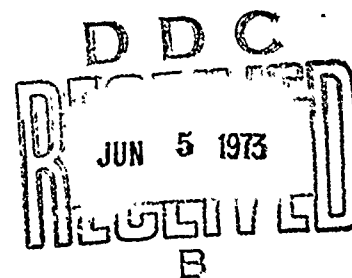
PART I. INERTIAL IMPACTION THEORY

by

Arthur K. Stuempfle

Chemical Laboratory

March 1973



**DEPARTMENT OF THE ARMY
Headquarters, Edgewood Arsenal
Aberdeen Proving Ground, Maryland 21010**

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EDGEWOOD ARSENAL TECHNICAL REPORT

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IMPACTION EFFICIENCY OF CYLINDRICAL COLLECTORS IN LAMINAR
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Task 1W062116A08402

DEPARTMENT OF THE ARMY
Headquarters, Edgewood Arsenal
Aberdeen Proving Ground, Maryland 21010

FOREWORD

The work described in this report was authorized under Task IW062116A08402, Chemical Test and Assessment Technology. This work was started in March 1971 and completed in February 1972.

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Acknowledgment

The author wishes to acknowledge the assistance of SP5 John Florence and SP4 William Saunders in preparation of the computer program for the particle path determination.

DIGEST

The theory of inertial impaction of particles on cylinders has been extended to include small inertial parameter values of interest in chemical operations. Digital computer techniques have been applied to accurately calculate particle trajectories and impaction efficiencies of small particles (10 to 100 μm in diameter) on man-sized collectors. The results are generalized in graphic form of impaction efficiency versus the inertial parameter. These data are compared with results of previous investigators; namely, Langmuir and Blodgett, and Brun, Lewis, Perkins, and Serafini. Significant differences in impaction efficiency are noted for small inertial parameter values. The data agree within 1% for inertial parameter values exceeding one. Theoretical data indicate that the Stokes' law region for defining the drag force on a particle can be exceeded at some point in the trajectory path for all circumstances of interest in chemical operations.

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IMPACTION EFFICIENCY OF CYLINDRICAL COLLECTORS IN LAMINAR AND TURBULENT FLUID FLOW

PART I. INERTIAL IMPACTION THEORY

I. INTRODUCTION.

Inertial impaction is a principal mechanism by which intermediate-size particles (10 to 100 μm in diameter) are deposited on collectors placed in a fluid flow field. Inertial impaction theory is fundamental in effectiveness studies of chemical operations and has been used to predict the mass deposited on cylindrical elements exposed to aerosol clouds in the free atmosphere. The theory, in most circumstances, predicts zero collection efficiency for the impaction of small particles on man-sized targets under field conditions. Experimental measurements, however, reveal that significant deposits can occur and it has been postulated* that atmospheric turbulence is a major causal factor influencing the collection efficiency. A theoretical and experimental program has, therefore, been undertaken to clarify the effects of turbulence on the impaction of liquid droplets on cylindrical collectors.

Simplified theoretical estimates of the impaction efficiency of circular cylinders began with Albrecht¹ and Sell² after World War I. The first comprehensive analysis of the impaction efficiency of particles on infinitely long circular cylinders under ideal fluid flow conditions was made by Langmuir and Blodgett.³ These authors used a mechanical differential analyzer to compute the motion of particles around a cylinder placed in a steady, frictionless, incompressible fluid. Brun, Lewis, Perkins, and Serafini⁴ repeated the computations of Langmuir and Blodgett for a cylinder using a larger and, presumably, more accurate mechanical differential analyzer. The methodology used by the latter authors has served as the basis for numerous investigations cited and reviewed by Fuchs⁵ and Golovin and Putnam.⁶ Consideration of the influence of viscosity on the flow field and of the interception phenomenon associated with the finite size of the impacting particles has been undertaken by Davies and Peetz,⁷ Landahl and

*Bernard Gerber. Private communication. Chemical Laboratory, Edgewood Arsenal. 1965.

¹ Albrecht, F. Theoretische Untersuchungen über die Ablagerung von Staub aus strömender Luft und ihre Anwendung auf die Theorie der Staubfilter. *Physik. Z.* 32, 48 (1931). Translated by P. J. Domotor, AEC Contract AT(30-3)-28, Report SO-1004, 1951.

² Sell, W. Ablagerungen an einfachen Körpern. *Forsch. Gebiete Ingenieurw.* 2, Forschungsheft, 347 (August 1931). Translated by P. J. Domotor, AEC Contract AT(30-3)-28, Report SO-1004, 1951.

³ Langmuir, I., and Blodgett, K. B. Army Air Forces Air Materiel Command, Technical Report 5418. A Mathematical Investigation of Water Droplet Trajectories. Contract W-33-038-ac-9151. General Electric Company. February 19, 1946 UNCLASSIFIED Report.

⁴ Brun, R. J., Lewis, W., Perkins, P. J., and Serafini, J. S. Impingement of Cloud Droplets on a Cylinder and Procedure for Measuring Liquid-Water Content and Droplet Sizes in Supercooled Clouds by Rotating Multicylinder Method. National Advisory Committee for Aeronautics Report 1215, 1955.

⁵ Fuchs, N. A. The Mechanics of Aerosols. Chapters II and IV. p 164. Pergamon Press Book. The Macmillan Company, New York, New York. 1964.

⁶ Golovin, M. N., and Putnam, A. A. Inertial Impaction on Single Elements. *Ind. Eng. Chem. Fundam.* 1, 264 (1962).

⁷ Davies, C. N., and Peetz, C. V. Impingement of Particles on a Transverse Cylinder. *Proc. Roy. Soc. (London)* A234, 269 (1956).

Herrmann,⁸ Ranz and Wong,⁹ and more currently by Householder and Goldschmidt.¹⁰ Potential flow theory, however, has been found to adequately represent a laminar flow field when the Reynolds number of the collector is greater than approximately one thousand.

The theoretical results obtained by Langmuir and Blodgett and by Brun, *et al.*, and the recent experimental data of May and Clifford¹¹ are presented in the form of curves of impaction efficiency versus a dimensionless scaling factor termed the inertial parameter. These curves, in themselves, constitute the inertial impaction theory for cylinders in a field described by potential flow theory. It is notable that the inherent inaccuracies of analog computation preclude the computation of the collection efficiency at small values of the scaling factor. The impaction efficiency curves, therefore, do not encompass particle inertial parameter values of interest to many chemical operation circumstances and do not account for natural effects such as turbulence. An accurate calculation of the particle trajectories around cylinders in potential flow is basic to the analysis of particle impaction under turbulent flow conditions as suggested by Torgeson.¹² Consequently, the objectives of this report have been to extend the impaction efficiency curves for low inertial parameter values and to accurately calculate the trajectories of particles around cylinders in potential flow by use of digital computer techniques.

II. INERTIAL IMPACTION THEORY.

A. General.

The theory of inertial impaction is concerned with the motion of suspended particles transported past a stationary cylinder positioned in a flow field. Several forces come into play as the particle-laden airstream approaches the cylinder. The airstream diverges along the stagnation line in order to bypass the collector. The diverging fluid attempts to change the particle direction by exerting a drag force on the particle. The inertia of the particle tends to maintain the straight-line motion of the particle as the airstream diverges around the bluff body. The trajectories of some of the deflected particles will miss the collector while other trajectories, which cannot follow the airstream, will intersect the cylinder surface. The efficiency of impaction is defined as the ratio of the cross-sectional area of the original aerosol stream from which the trajectories of the particles intersect the collector surface to the projected area of the cylindrical collector in the direction of flow. Simply stated, the impaction efficiency is the ratio of the number of particles that hit the collector to the number of particles that would hit if the

⁸ Landahl, H. D., and Herrmann, R. G. Sampling of Liquid Aerosols by Wires, Cylinders, and Slides, and the Efficiency of Impaction of the Droplets. *J. Colloid Sci.* 4, 103 (1949).

⁹ Ranz, W. E., and Wong, J. B. Impaction of Dust and Smoke Particles on Surface and Body Collectors. *Ind. Eng. Chem.* 44, 1371 (1952).

¹⁰ Householder, M. K., and Goldschmidt, V. W. The Impaction of Spherical Particles on Cylindrical Collectors. *J. Colloid Interface Sci.* 31, 464 (1969).

¹¹ May, K. R., and Clifford, R. The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons and Discs. *Ann. Occupational Hyg.* 10, 83 (1967).

¹² Torgeson, W. L. Applied Science Division, Litton Systems, Inc. Summary Report - Phase II. Contract DA-18-035-AMC-340(A). Investigation of Impaction Mechanisms of Particles on Collectors in Turbulent Flow (U). August 1967. CONFIDENTIAL Report.

stream lines had not been diverted. If all particles that impact on the surface adhere to the collector, then the impaction efficiency equals the collection efficiency of the cylinder.

B. Mathematical Formulation.

Mathematical formulation of the inertial impaction problem is accomplished in the following manner:

The instantaneous hydrodynamical drag force on a spherical body moving in an infinite fluid field is generally written as:

$$F_D = C_D \rho_a \pi a^2 (\bar{v})^2 / 2 \quad (1)$$

where

F_D = drag force

C_D = dimensionless drag coefficient for spherical particles in air

ρ_a = density of air

a = particle radius

\bar{v} = local vector difference between air velocity and particle velocity

The Reynolds number of the particle with respect to the local relative velocity is

$$Re = \frac{2a\rho_a\bar{v}}{\mu} \quad (2)$$

where μ = viscosity of the fluid.

The drag force is therefore expressed as

$$F_D = \frac{C_D Re}{4} \pi a \mu \bar{v} \quad (3)$$

From Newton's second law of motion, the equations of motion for a spherical droplet in Cartesian coordinates are written as:

$$\frac{4}{3} \pi a^3 \rho \frac{dv'_x}{dt} = \frac{C_D Re}{4} \pi a \mu (u'_x - v'_x) + E_x \quad (4a)$$

$$\frac{4}{3} \pi a^3 \rho \frac{dv'_y}{dt} = \frac{C_D Re}{4} \pi a \mu (u'_y - v'_y) + E_y \quad (4b)$$

where

- ρ = density of particle
- x_1, y_1 = Cartesian coordinates
- u'_x, u'_y = x_1 and y_1 components of airstream velocity, respectively
- v'_x, v'_y = x_1 and y_1 components of particle velocity, respectively
- E_x, E_y = Cartesian components of external forces acting on the particle

For this report, external forces on the particle due to gravity and electrostatic effects have been neglected.

Equations 4a and 4b can be put into dimensionless form by the methodology proposed by Langmuir and Blodgett;³ namely,

$$\left(\frac{2}{9} \frac{\rho a^2 \bar{U}}{\mu R}\right) \frac{R}{\bar{U}^2} \frac{dv'_x}{dt} = \frac{C_D Re}{24} \frac{(u'_x - v'_x)}{\bar{U}} \quad (5)$$

$$\left(\frac{2}{9} \frac{\rho a^2 \bar{U}}{\mu R}\right) \frac{R}{\bar{U}^2} \frac{dv'_y}{dt} = \frac{C_D Re}{24} \frac{(u'_y - v'_y)}{\bar{U}}$$

where

- \bar{U} = free-stream velocity at an infinite distance from the cylinder surface
- R = cylinder radius

which reduce to

$$\frac{dv_x}{d\tau} = \frac{C_D Re}{24} \frac{1}{K} (u_x - v_x) \quad (6)$$

$$\frac{dv_y}{d\tau} = \frac{C_D Re}{24} \frac{1}{K} (u_y - v_y)$$

where

$$K \equiv \frac{\rho d_p^2 \bar{U}}{18 \mu R} \quad (7)$$

d_p = particle diameter

τ = $\frac{\bar{U}}{R} t$ = time scale

and the velocity components have been normalized by the free-stream velocity. Following the convention of Langmuir and Blodgett, the parameter K is defined as the ratio of the "stopping" distance of a particle projected with velocity \bar{U} into still air (assuming Stokes' law of resistance) to the cylinder radius; i.e.,

$$K = \lambda_s / R$$

where $\lambda_s = \text{stopping distance} = \frac{\rho d_p^2 \bar{U}}{18\mu}$.

K is a measure of the inertia of the particle and relates to the magnitude of the external force required to cause a change in its direction of motion. This variable is subsequently termed the inertial parameter.

Inertial parameter values of interest in chemical operations can be calculated through stylizing a particle target into a composite of circular cylinders.^{13,14} Assuming that the impacting particle is of unit density and the ambient air viscosity is 1.81×10^{-4} poise, equation 7 reduces to

$$K = 1.37 \times 10^{-4} \frac{d_p^2 \bar{U}}{R} \quad (7a)$$

where

\bar{U} = windspeed (mph)

d_p = particle diameter (μm)

R = cylinder radius (cm)

Representative K values are shown in table I.

Equation 2 can be expressed as

$$\text{Re} = \frac{d_p \rho_a}{\mu} \sqrt{(u'_x - v'_x)^2 + (u'_y - v'_y)^2} \quad (2a)$$

¹³ Magram, S. J. CWL Technical Memorandum 5-1. CARAMU Note No. 1. Impaction Efficiency of Aerosol Particles. 15 January 1958. UNCLASSIFIED Report.

¹⁴ McIntyre, J., and Lipps, R. D. Operations Research, Incorporated, Silver Spring, Maryland Technical Note 64-45. Collection Efficiency of Soldiers in the Field. September 1964. UNCLASSIFIED Report.

Table I. Inertial Parameter Values, K (20°C)

Cylinder diameter	Windspeed	Inertial parameter K			ϕ Parameter value
		Particle diameter			
		20 μ m	50 μ m	100 μ m	
cm	mph				
35 (Body)	3	0.009	0.059	0.235	339
	6	0.019	0.118	0.470	677
	10	0.031	0.196	0.784	1129
20 (Legs)	3	0.016	0.103	0.412	194
	6	0.033	0.206	0.823	387
	10	0.055	0.343	1.37	645
16 (Head)	3	0.021	0.129	0.514	155
	6	0.041	0.257	1.03	310
	10	0.068	0.428	1.72	516
8 (Arms)	3	0.041	0.257	1.03	77
	6	0.082	0.514	2.05	155
	10	0.137	0.856	3.42	258
2 (Fingers)	3	0.164	1.03	4.11	19
	6	0.329	2.06	8.22	39
	10	0.548	3.43	13.70	65

As noted by Brun, *et al.*,⁴ it is convenient for computational purposes to define a free-stream Reynolds number for the particle as

$$Re_0 = \frac{d_p \rho_a \bar{U}}{\mu} \quad (8)$$

Although Re_0 is the Reynolds number of a particle moving with velocity \bar{U} in still air, it is not intended to suggest relative motion between the particle and the free-stream air but rather to serve as a velocity scaling parameter.

Equation 2a can therefore be normalized with respect to the free-stream velocity and can be rewritten in terms of the free-stream Reynolds number of the particle as

$$\left(\frac{Re}{Re_0} \right)^2 = (u_x - v_x)^2 + (u_y - v_y)^2 \quad (9)$$

Langmuir and Blodgett introduced a second dimensionless parameter, ϕ , for computational purposes, that proved to be useful in interpretation of experimental data on icing and rime formation. The parameter is defined in terms of the free-stream Reynolds number of the particle and the inertial parameter as

$$\phi \equiv \frac{Re_p^2}{K} = \frac{18\rho_a^2 \bar{U}R}{\mu\rho} \quad (10)$$

Moreover, ϕ can also be written in terms of the Reynolds number of the collector as

$$\phi = \left(\frac{9\rho_a}{\rho} \right) \frac{\rho_a 2R\bar{U}}{\mu} = \frac{9\rho_a}{\rho} (Re_c)$$

where Re_c = Reynolds number of the cylindrical collector.

Note that ϕ turns out to be independent of the particle size. Previous authors simply note the significance of the ϕ parameter by stating that its magnitude is a measure of the deviation from Stokes' law due to the forces acting on the particle. However, interpretation of the ϕ parameter is more fundamental than this.

The ϕ parameter is used to obtain the magnitude of relative velocity for the instantaneous Reynolds number of the particle in the flow field which yields the instantaneous drag force acting on the particle. In essence, ϕ "unscales" the velocity components of the particle and the flow field throughout the trajectory path followed by the particle.*

Stokes' law is valid only for very small Reynolds numbers ($Re < 0.1$) where inertia effects resulting from displacement of air by the particle are negligible. Only with small collectors at low windspeeds ($\phi \rightarrow 0$) will small particles (low inertial parameter values) obey Stokes' law throughout its entire trajectory. By convention, however, $\phi = 0$ defines the circumstance in which the particle precisely obeys Stokes' law everywhere in its trajectory; i.e., $C_D Re / 24 = 1$. The ϕ parameter value is generally substantially greater than one for most conditions encountered in chemical operations and must be taken into account in impaction efficiency calculations. Representative values of ϕ corresponding to their respective inertial parameter values are given in table I.

A mathematical description of the flow field around the cylinder is required in order to solve the foregoing trajectory equations of particle motion. Potential fluid flow theory can be used to obtain the air-velocity components about a cylinder when the Reynolds number with respect to the collector is greater than one thousand. Based upon the conditions presented in table 1, the minimum Reynolds number is approximately 1777 for the 2-cm-diameter collector in a 3-mph airstream. Therefore, in the absence of turbulence, potential flow is an adequate approximation to the actual flow of the airstream.

*Bernard Gerber. Private communication. Chemical Laboratory, Edgewood Arsenal. 1971.

Consider a stationary cylinder of radius R of infinite length immersed in a fluid of infinite extent having a free-stream velocity, \bar{U} . Assume that the fluid is ideal ($\rho_a = \text{constant}$ and $\mu = 0$) and that the flow is without circulation. The stream function for potential flow about a cylinder is then given by^{1,5}

$$\psi_1(x_1, y_1) = -\bar{U}y_1 \left(1 - \frac{R^2}{(x_1)^2 + (y_1)^2} \right)$$

where x_1, y_1 are Cartesian coordinates of a point in the fluid. In terms of dimensionless quantities

$$\psi(X, Y) = -Y \left(1 - \frac{1}{X^2 + Y^2} \right)$$

where

$$\psi = \psi_1(x_1, y_1)/\bar{U}R$$

X, Y = Cartesian coordinates normalized with respect to the cylinder radius.

The normalized velocity components of the fluid at X and Y are

$$u_X = -\frac{\delta \psi}{\delta Y} \quad \text{and} \quad u_Y = \frac{\delta \psi}{\delta X}$$

so that the velocity components of the flow field in front of the collector can be expressed as

$$u_X = 1 + \frac{Y^2 - X^2}{(X^2 + Y^2)^2} \quad (11)$$

and

$$u_Y = -\frac{2XY}{(X^2 + Y^2)^2} \quad (12)$$

Time is again expressed in dimensionless form as $\tau = \frac{t\bar{U}}{R}$, and the airstream is assumed to approach the cylinder parallel to the X -axis and from a negative X -direction.

C. Input Data Requirements.

The values of $C_D Re/24$ as a function of Re must be known in order to numerically solve the differential equations of motion described by equations 6 through 12. This is necessary because the values of the velocity components are variables whose magnitude is a function of the position of the particle in the flow field. Langmuir and Blodgett used drag coefficient values determined from an empirical curve and their data values (extrapolated when necessary) are listed in table II. As the relative motion between the particle and air approaches zero as a limiting case, the value of $C_D Re/24$ approaches unity. Stokes' resistance law for the drag force on a sphere applies exactly when $C_D Re/24 = 1$. Fuchs¹⁵ has compiled a table of values for the drag function based on experimental measurements that he considered to be reliable. The probable error in drag coefficient is claimed to be less than 1% for $Re < 0.5$ and increases to a maximum of 4% at $Re = 500$. Fuchs' table of values has been interpolated for use in this study and is given in table III. Figure 1 compares the Langmuir and Blodgett data with the Fuchs' data.

Table II. Langmuir and Blodgett Drag Coefficient Data

Re	$C_D Re/24$	Re	$C_D Re/24$	Re	$C_D Re/24$
0	1.0000	2.0	1.285	60	3.60
0.01	1.0019	2.5	1.332	80	4.11
0.02	1.0036	3.0	1.374	100	4.59
0.03	1.0055	3.5	1.412	120	5.01
0.04	1.0073	4.0	1.447	140	5.40
0.05	1.0090	4.5	1.480	160	5.76
0.06	1.0109	5.0	1.513	180	6.16
0.07	1.0128	6.0	1.572	200	6.52
0.08	1.0146	7.0	1.625	250	7.38
0.09	1.0165	8.0	1.678	300	8.26
0.10	1.018	9.0	1.725	350	9.00
0.12	1.022	10	1.782	400	9.82
0.153	1.028	11	1.850	500	11.46
0.20	1.037	12	1.901	600	12.97
0.25	1.045	14	2.009		
0.30	1.055	16	2.109		
0.40	1.073	18	2.198		
0.50	1.092	20	2.291		
0.60	1.103	22	2.375		
0.80	1.142	25	2.489		
1.0	1.176	30	2.673		
1.2	1.201	35	2.851		
1.4	1.225	40	3.013		
1.6	1.248	45	3.170		
1.8	1.267	50	3.327		

$$\text{where } Re = \frac{\rho_a d_p \bar{v}}{\mu}$$

¹⁵ Bird, R. B., Stewart, W. E., and Lightfoot, E. N. Transport Phenomena. John Wiley & Sons, Inc., New York, New York. 1960.

Table III. Fuchs' Drag Coefficient Data

Re	$C_D Re/24$	Re	$C_D Re/24$	Re	$C_D Re/24$
0	1.0000	1.58	1.1852	45.00	3.1630
0.005	1.0000	1.80	1.2050	50.12	3.2945
0.0098	1.0010	2.00	1.2268	63.10	3.6542
0.0145	1.0020	2.51	1.2758	79.43	4.0718
0.020	1.0031	3.16	1.3360	88.00	4.2800
0.030	1.0052	3.50	1.3651	100.0	4.5582
0.040	1.0071	3.98	1.4054	125.9	5.1379
0.050	1.0089	4.50	1.4450	158.5	5.8182
0.063	1.0111	5.01	1.4852	199.5	6.6342
0.072	1.0124	6.31	1.5768	251.2	7.5996
0.079	1.0134	7.00	1.6250	316.2	8.7657
0.090	1.0147	7.94	1.6819	398.1	10.1575
0.100	1.0158	9.00	1.7400	501.2	11.8519
0.126	1.0204	10.00	1.8021	631.0	13.8928
0.158	1.0252	11.00	1.8510		
0.200	1.0299	12.59	1.9399		
0.251	1.0346	14.00	2.0200		
0.316	1.0418	15.85	2.0979		
0.398	1.0515	18.00	2.2150		
0.501	1.0636	19.95	2.2792		
0.631	1.0784	23.00	2.4210		
0.794	1.0985	25.12	2.4819		
1.00	1.1215	31.62	2.7151		
1.26	1.1502	35.00	2.8520		
1.40	1.1670	39.81	2.9839		

$$\text{where } Re = \frac{\rho_a d_p \bar{v}}{\mu}$$

The Cartesian coordinate system used in this study is identical to that of Brun, *et al.*,⁴ and is shown in figure 2. The motion of the particles is in a plane perpendicular to the cylinder axis which is the origin of the coordinate system. Simplifying assumptions that have been made in the derivations and in computing the trajectory of a particle are:

1. At an infinite distance in front of the cylinder, the particles have horizontal and vertical velocity components equal to the free-stream air.
2. The particles are spherical, monometric (uniform size), and monodisperse (single particles), and they do not evaporate or deform.
3. Gravitational, electrostatic, and any other external forces are negligible.
4. The particle radius is negligible with respect to the cylinder radius (interception effect neglected).
5. The boundary layer about the cylinder surface does not affect the particle trajectory.
6. The airflow around the cylinder is described as ideal and without circulation and is unaffected by the presence of the particles.

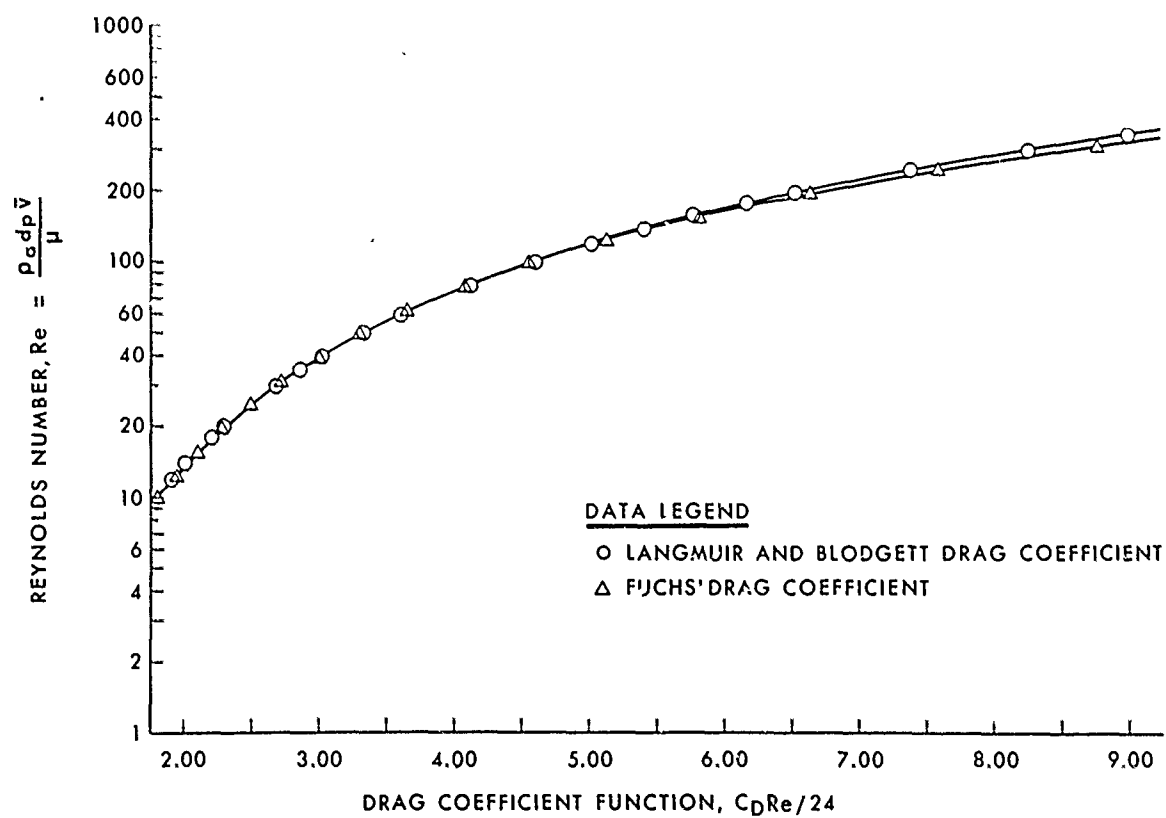
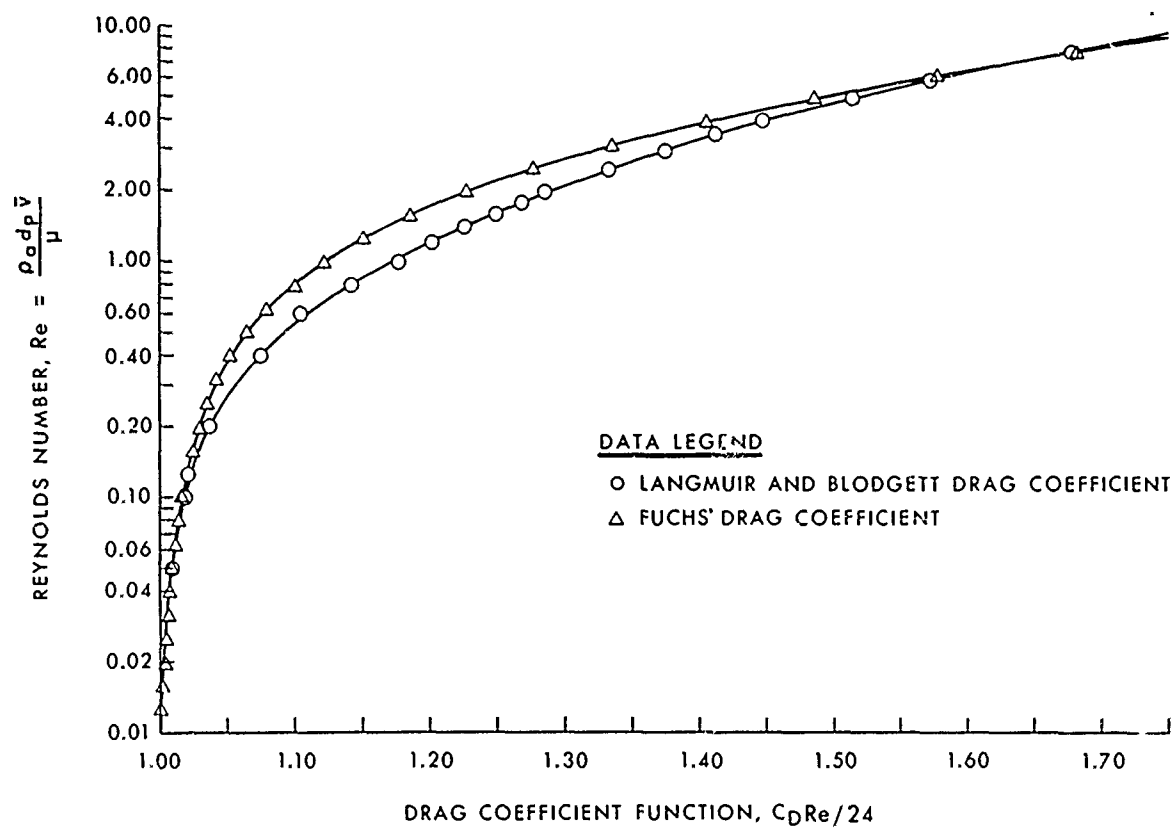


Figure 1. Comparison of Drag Coefficient Data of Fuchs with That of Langmuir and Blodgett

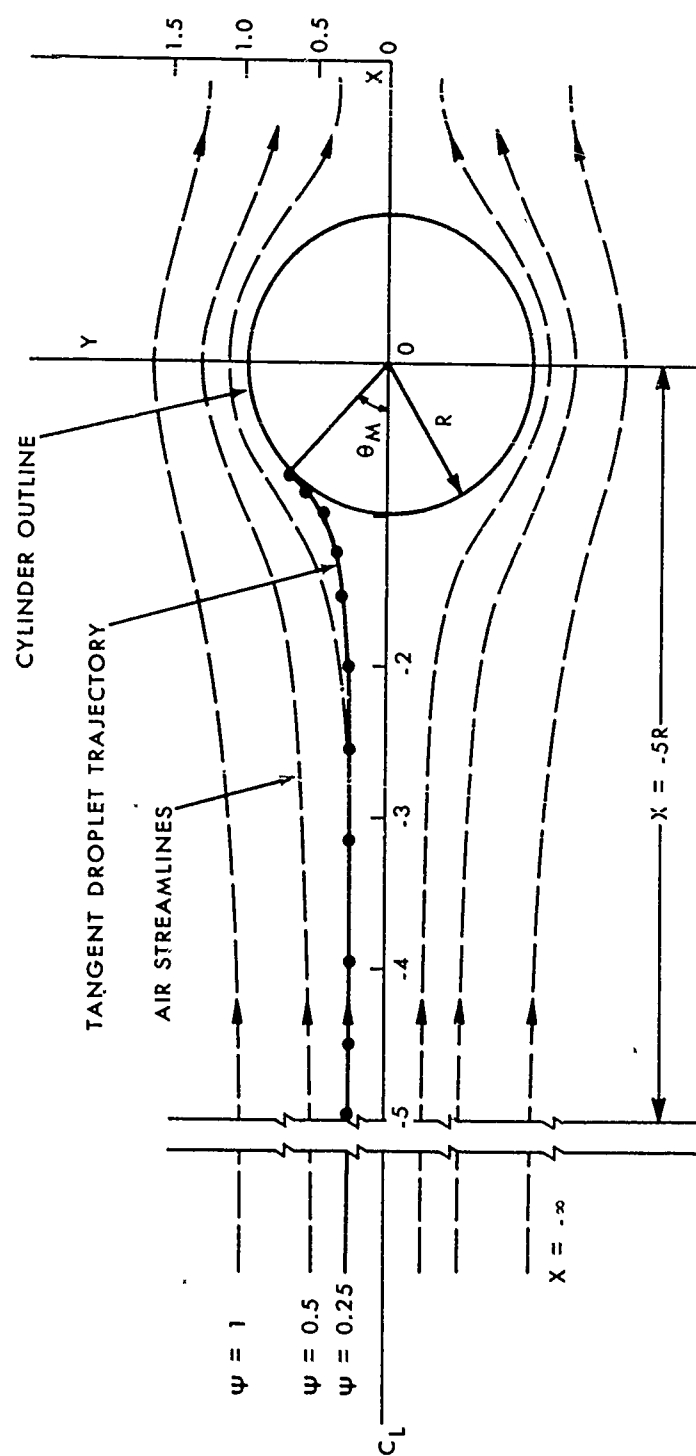


Figure 2. Coordinate System for Cylinder in Potential Flow Field

7. The instantaneous drag force coefficient for the particle is given by the steady-state data and is not subjected to acceleration effects.

8. All particles that strike the collector surface adhere to it.

The equations of motion given above have been programmed for step-by-step integration by digital computer techniques. A description of the general methodology is contained in appendix A. Particle trajectory calculations were begun at five radii in front of the cylinder centerline and initial conditions were obtained with the formulas suggested by Torgeson.¹² These approximations differ from the Langmuir and Blodgett³ equations through the retention of higher order terms. Derivations of starting condition formulas are found in appendix B.

III. RESULTS AND DISCUSSION.

Results of the digital computer trajectory calculations to determine the efficiency of impaction of particles on cylindrical collectors in an ideal flow field are shown in figure 3. The impaction data for inertial parameter values less than one are displayed in figure 4. In addition to the impaction efficiency, the maximum angle of impingement, θ_m , beyond which, theoretically, no deposition occurs by the inertial mechanism, has been computed and plotted in figure 5. The computational results reported in figures 3, 4, and 5 have been obtained by use of the Fuchs' drag coefficient data with initial trajectory starting conditions begun at 5 radii upstream of the cylinder axis (see appendix B). These data are included in appendix C. It is believed that these results are more accurate than those previously reported,^{3,4,12} especially in the small inertial parameter region.

Table IV compares numerical values of the impaction efficiency and maximum impingement angle obtained from this study (AKS) with the data of Brun and Associates (NACA) and of Langmuir and Blodgett (L&B). The more significant differences occur at inertial parameter values less than one, as anticipated. The differences that take place for $K > 1$ are not major and are variable depending on the particular K and ϕ parameter for the case in question. The minor differences for $K > 1$ are due in large part to use of Fuchs' drag coefficient data for spherical particles.

The particle trajectory calculations were repeated using the Langmuir and Blodgett drag coefficients and their initial trajectory starting conditions (appendix B). The calculated impaction efficiencies were found to correspond within $\approx 1\%$ to the Langmuir and Blodgett efficiency data for $K > 1$. Results of these computations are included in appendix D. Brun and coworkers do not explicitly list the drag coefficient data used in their theoretical study, but, presumably, they were the same as those of Langmuir and Blodgett. However, specific differences in impaction efficiency are observed and are believed due to the initial starting velocity conditions and particular particle trajectory tracing procedure (see appendix B).

Determination of the particle trajectories requires a knowledge of the particle velocity when integration is started. Conventional calculations have been initiated at 5 radii upstream of the cylinder axis and the particle equations of motion (equation 6) have been

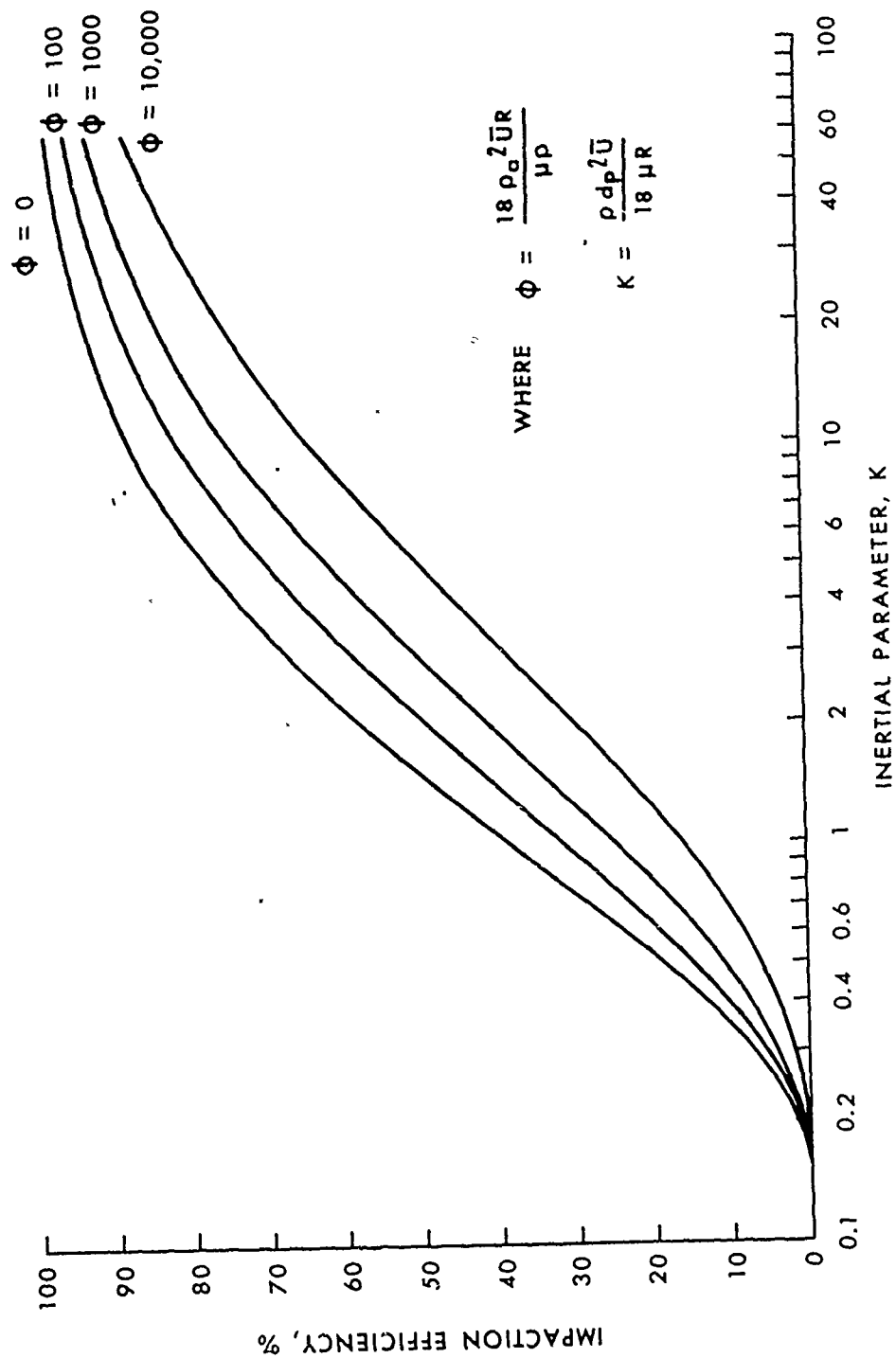


Figure 3. Impaction Efficiency for Cylinders

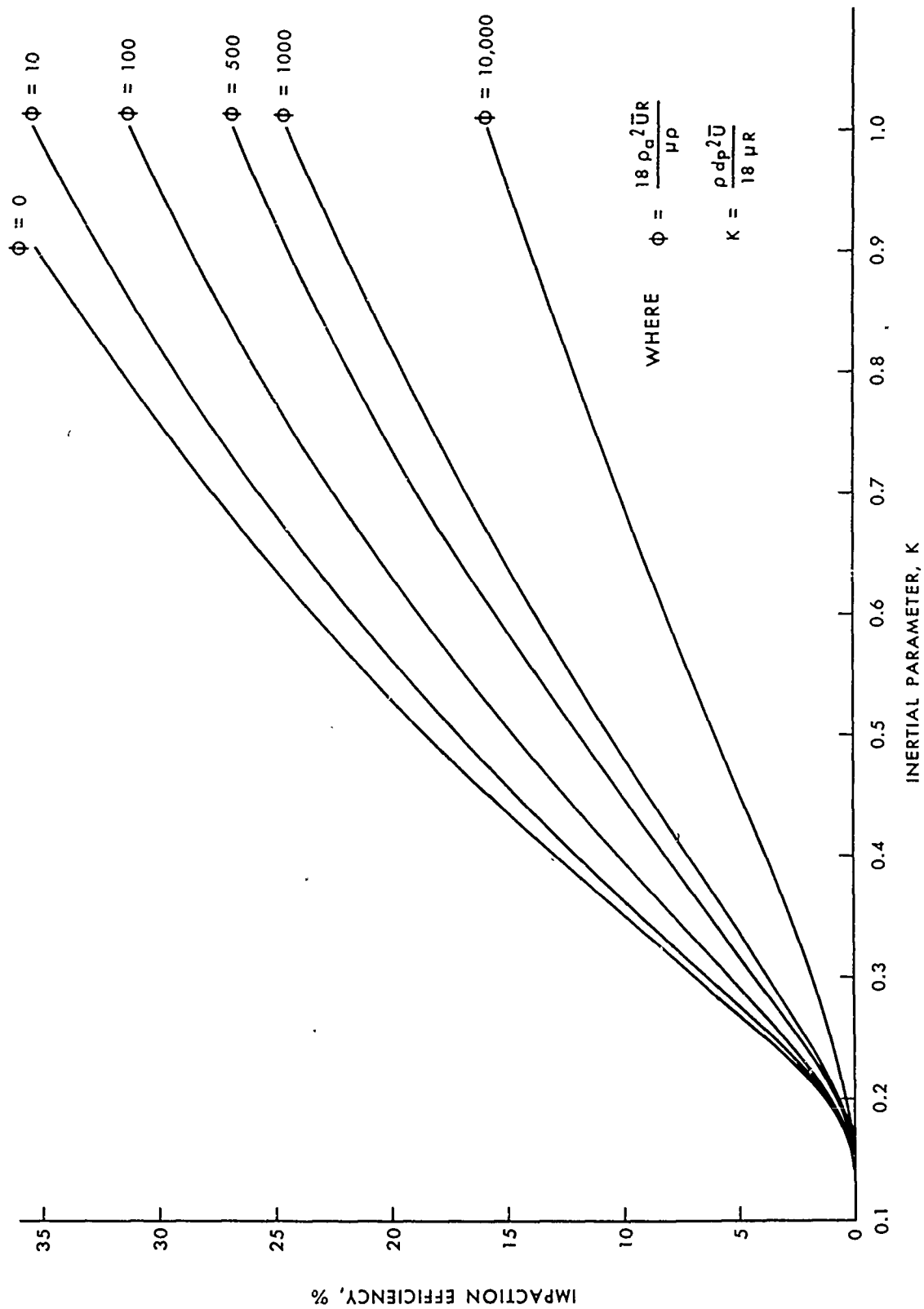


Figure 4. Impact Efficiency for Cylinder for $K \leq 1.0$

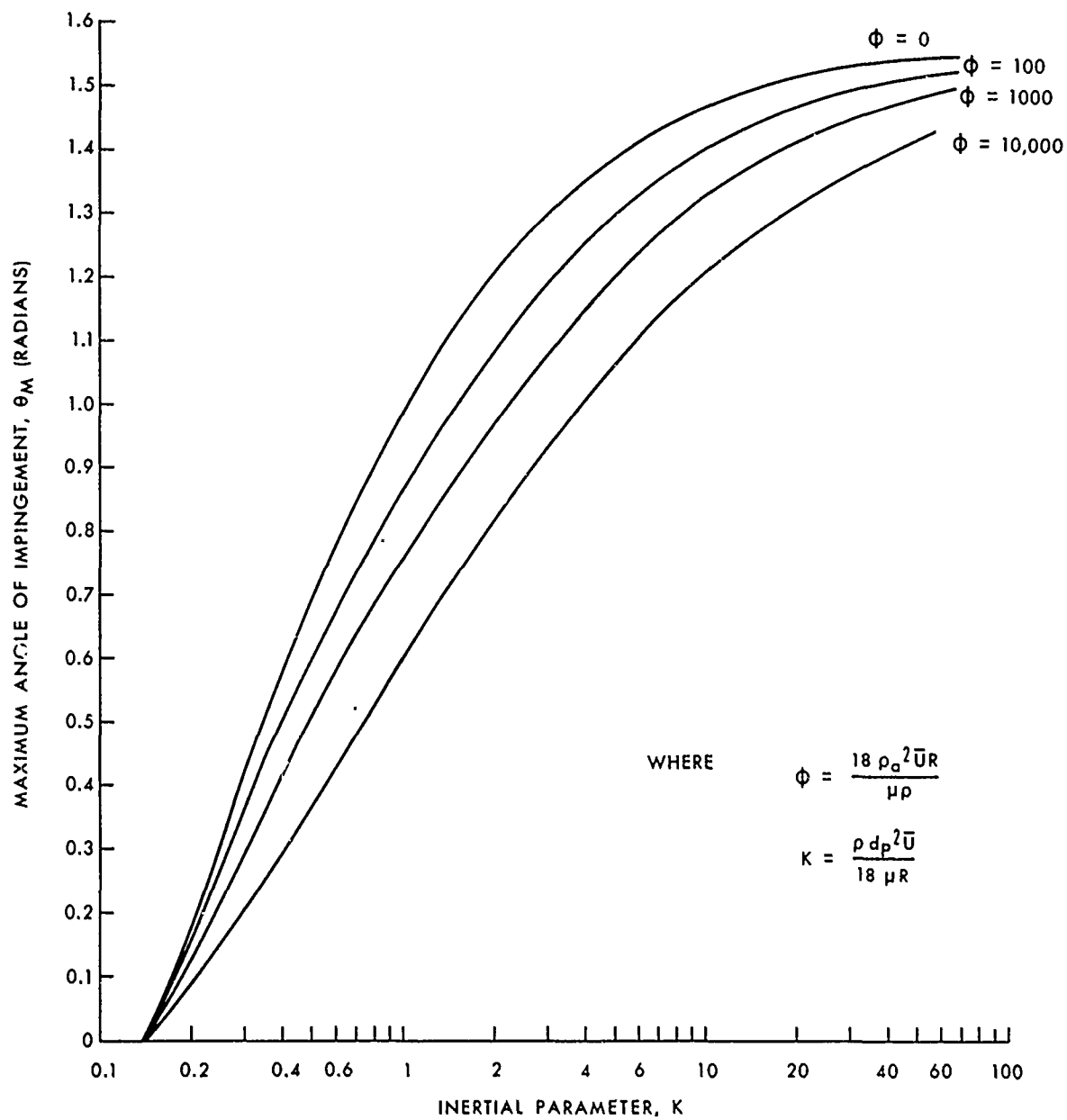


Figure 5. Maximum Angle of Impingement on Cylinders

Table IV. Impaction Efficiency Comparison of AKS, NACA, and L&B Theoretical Data

ϕ	K	Impaction efficiency			Maximum angle of impingement		
		E (AKS)	E (NACA)	E (L&B)	θ_M (AKS)	θ_M (NACA)	θ_M (L&B)
					radians		
0	0.175	0.005	-	0.013	0.105	-	0.175
	0.25	0.039	0.051	0.042	0.313	0.330	0.340
	0.50	0.186	0.205	0.186	0.691	0.716	0.688
	1	0.382	0.380	0.380	0.987	0.980	0.991
	4	0.734	0.741	0.722	1.358	1.379	1.365
	16	0.915	0.920	0.909	1.506	1.518	1.517
	40	0.963	0.957	0.962	1.547	1.538	1.546
100	0.175	0.004	-	0.008	0.095	-	0.148
	0.50	0.148	0.157	0.127	0.605	0.601	0.565
	1	0.313	0.309	0.296	0.878	0.865	0.857
	4	0.649	0.680	0.639	1.253	1.291	1.253
	40	0.931	0.924	0.928	1.511	1.522	1.504
1000	0.175	0.003	-	-	0.079	-	0.122
	0.50	0.107	0.116	0.090	0.503	0.504	0.483
	1	0.245	0.250	0.228	0.762	0.760	0.719
	4	0.567	0.616	0.568	1.154	1.20	1.147
	16	0.808	0.830	0.806	1.390	1.445	1.391
10,000	0.175	0.001	-	-	0.055	-	0.103
	0.50	0.060	0.070	0.053	0.378	0.385	0.384
	1	0.158	0.157	0.156	0.603	0.595	0.597
	4	0.446	0.480	0.441	1.010	1.060	0.997
	16	0.713	0.755	0.710	1.285	1.345	1.286

linearized by the approximations given in appendix B for the region between $X = -\infty$ and $X = -5$. At approximately 3 radii upstream of the cylinder axis, the velocity components of the airstreams, defined by equations 11 and 12, undergo rapid deviation from their velocity at large distances ahead of the cylinder. The impaction efficiencies have been calculated by considering initial trajectory starting conditions of $X = -3$, -5 , and -10 radii upstream. Results of these computations are included in appendix E.

The computations performed in this study have not been extended over the extreme ranges reported by previous authors because large inertial parameter and ϕ parameter values are rarely of interest in chemical operations.

Figure 6 provides a convenient graph for evaluating the ϕ parameter and has been prepared after assuming ambient temperature conditions of 20°C and unit density droplets. The ϕ parameter value corresponding to a 35-cm-diameter (body) collector in a 20-mph wind is less than 2500 and ϕ values greatly exceeding this number would not be expected to occur in usual chemical operations. The trajectory data reveal that, in all cases where $\phi \geq 1$, the Reynolds

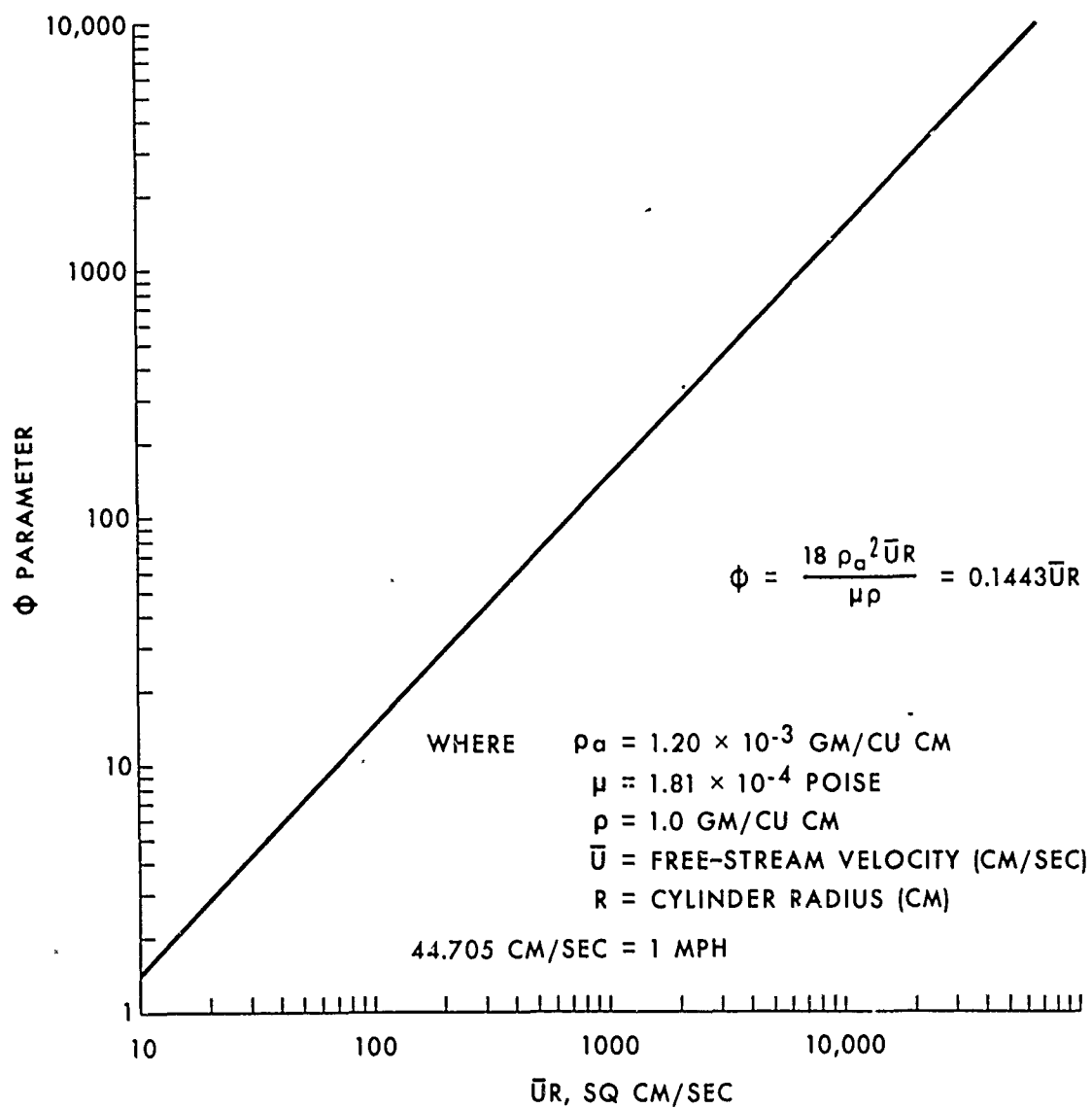


Figure 6. ϕ Parameter for Ambient Temperature (20°C) and Unit Density Particles

number of the particle that barely escapes impaction will at some point in its trajectory assume values exceeding the region for Stokes' law validity. As noted earlier, the $\phi = 0$ impaction efficiency curve is an artifact corresponding to a maximum value for the impaction efficiency in the absence of turbulence. It must also be kept in mind that the steady-state drag curve has been assumed to apply for the respective instantaneous relative velocity at each point in the particle trajectory.

The family of impaction efficiency curves (figures 3 and 4) tends to approach a common inertial parameter value below which, theoretically, no deposition occurs by the inertial mechanism. Langmuir and Blodgett analytically determined the critical condition for zero deposition efficiency by considering the airstream velocity in the vicinity of the stagnation point of cylinders to be a linear function of distance. Their analysis shows that, when inertial parameter values exceed 0.125, particles impact at the stagnation point with a finite velocity, whereas, if K is less than 0.125, no particles impact, theoretically. The critical condition for zero deposition efficiency can only be approached by the trajectory tracing routine developed herein due to computational accuracy. Zero deposition (considered as efficiency $< 10^{-5}$) was found to occur when $K \leq 0.130$ for all values of the ϕ parameter, which tends to support the critical cutoff hypothesis.

In reality, however, such a critical inertial parameter cutoff value may not exist because all particles have a finite size relative to the collector, the effects of which have not been considered for part I of this study. Further, other mechanisms for deposition, such as eddy diffusion and electrostatic forces, become important near the cutoff region. Ranz and Wong⁹ addressed the interception mechanism for ideal flow conditions and assumed that a particle will touch the cylinder whenever its center is within a distance $d_p/2$ of the surface. The minimum efficiency of impaction for a massless particle, but with a finite size ($K = 0$), is given as

$$E_0 = (1 + P) - 1/(1 + P) \quad (13)$$

where P = ratio of particle diameter to cylinder diameter.

The influence of a finite particle size on impaction efficiency by use of the digital computer trajectory tracing routines will be assessed and reported in part II of this series. It is anticipated that the interception mechanism will yield higher impaction efficiencies than predicted by equation 13 due to confluence of the trajectories at low inertial parameter values.

Calculated impaction efficiencies for stylized cylinders corresponding to the inertial parameter values of interest in chemical operations (table I) are given in table V. The minimum impaction efficiency by the interception mechanism (equation 13) has been included in parenthesis for those circumstances where the inertial impaction theory predicts zero efficiency or accuracy of the computation precludes a value. In practice, the deposition efficiency for inertial parameters less than 0.125 will be a function of the collector surface roughness and of the turbulence field. Experiments by Banfield and Russell¹⁶ and Asset, Kimball, and Hoff,¹⁷

¹⁶ Banfield, J. N., and Russell, J. H. Porton Note 39. August 1958. CONFIDENTIAL Report.

¹⁷ Asset, G., Kimball, D., and Hoff, M. EATR 4225. Small-Particle Collection Efficiency of Vertical Cylinders in Flows of Low-Intensity Turbulence. January 1969. UNCLASSIFIED Report.

Table V. Theoretical Impaction Efficiencies

Cylinder diameter	Windspeed	ϕ Parameter at 20°C	Theoretical impaction efficiency*		
			Particle diameter		
			20 μm	50 μm	100 μm
cm	mph		%		
35 (Body)	3	339	(0.011)	(0.029)	2.06
	6	677	(0.011)	(0.029)	10.33
	10	1129	(0.011)	0.64	18.77
20 (Legs)	3	194	(0.020)	(0.050)	10.06
	6	387	(0.020)	1.08	23.09
	10	645	(0.020)	5.75	33.46
16 (Head)	3	155	(0.025)	(0.062)	14.67
	6	310	(0.025)	2.92	28.98
	10	516	(0.025)	9.35	39.84
8 (Arms)	3	77	(0.050)	3.51	32.68
	6	155	(0.050)	14.67	48.38
	10	258	0.002 (0.050)	25.17	58.56
2 (Fingers)	3	19	0.22	35.34	69.28
	6	39	7.42	52.29	79.72
	10	65	17.47	62.82	85.21

* Numbers in parentheses equal minimum impaction efficiency by the interception mechanism from equation 13 for those circumstances where the inertial impaction theory predicts zero efficiency or accuracy of the computation precludes a value.

have shown that measurable collection efficiencies occur for very small inertial parameter values and that the efficiencies are dependent on the collector material. Of particular importance, the observed fact that turbulence can significantly increase the collection efficiency at small inertial parameter values is of considerable interest for chemical operations. An example of this effect is shown in figure 7. Clarification of the turbulence effects, therefore, begins with an accurate assessment of impaction under laminar flow conditions.

IV. CONCLUSIONS.

1. Digital computer techniques and revised drag coefficient data for spherical particles have been applied to calculate particle trajectories, impaction efficiencies, and maximum angles of impingement for cylinders in a potential flow field.

2. The theory of inertial impaction of particles on cylinders has been extended to include inertial parameter values relevant to chemical operations.

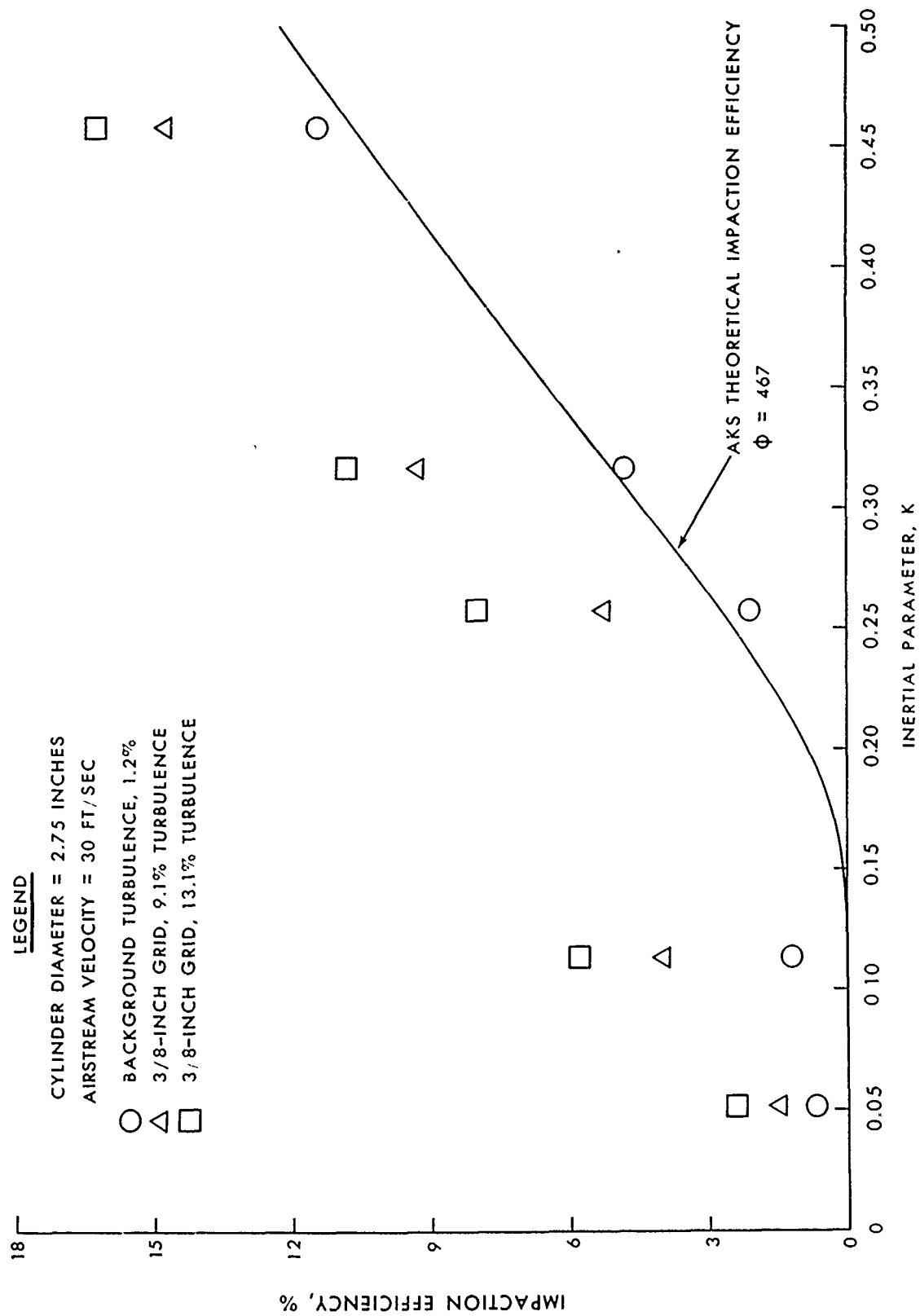


Figure 7. Experimental Impact Efficiency Under Turbulent Flow

3. The theoretical data have been compared with previous results of Langmuir and Blodgett and agree within 1% for inertial parameter values greater than one. Significant differences in impaction efficiency are observed for inertial parameter values less than one.

4. The inertial impaction theory for cylinders is presented as a family of curves of impaction efficiency versus inertial parameter for a wide variation of the dimensionless ϕ parameter.

5. Theoretical data indicate that the Stokes' law region for defining the drag force on a particle is exceeded at some point in its trajectory path for all circumstances of interest in chemical operations.

V. RECOMMENDATIONS.

1. The influence of the interception mechanism on impaction efficiency should be examined to determine the effects of confluence at low inertial parameter values.

2. An experimental program to assess impaction efficiency of particles on cylinders at low inertial parameter values under laminar and controlled turbulent flow conditions should be pursued.

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GLOSSARY

a	Particle radius
C_D	Drag coefficient for spherical particles in air
d_p	Particle diameter
E	Impaction efficiency
E_x, E_y	Cartesian components of external forces acting on particle
F_D	Drag force
$K = \frac{\rho_a d_p^2 \bar{U}}{18\mu R}$	Inertial parameter
P	Ratio of particle diameter to cylinder diameter
R	Cylinder radius
$Re = \frac{\rho_a d_p \bar{v}}{\mu}$	Reynolds number of particle with respect to local relative velocity
$Re_c = \frac{\rho_a 2R \bar{U}}{\mu}$	Free-stream Reynolds number of collector
$Re_o = \frac{d_p \rho_a \bar{U}}{\mu}$	Free-stream Reynolds number of particle
t	Time
\bar{U}	Free-stream velocity
u_x, u_y	Cartesian particle velocity components normalized by free-stream velocity
u'_x, u'_y	x_1, y_1 components of particle velocity, respectively
\bar{v}	Local vector difference between air velocity and particle velocity
v_x, v_y	Cartesian airstream velocity components normalized by free-stream velocity
v'_x, v'_y	x_1, y_1 components of airstream velocity, respectively
X, Y	Cartesian coordinates normalized by cylinder radius

x_1, y_1	Cartesian coordinates
θ_M	Maximum angle of impingement
λ_s	Stopping distance of particle under Stokes' law of resistance
μ	Fluid viscosity
ρ	Particle density
ρ_a	Air density
$\tau = \frac{\bar{U}t}{R}$	Time scale parameter
$\phi = \frac{Re_0^2}{K} = \frac{18\rho_a^2 \bar{U}R}{\mu\rho} = \frac{9\rho_a}{\rho} (Re_c)$	Dimensionless velocity field scaling parameter
$\psi(x,y)$	Stream function for potential fluid flow

APPENDIXES

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APPENDIX A

DESCRIPTION OF DIGITAL COMPUTER PROGRAM

The digital computer program developed for this study numerically integrates the equations of motion of the particle to calculate its trajectory around a cylinder in an ideal flow field. The input data necessary to determine the impaction efficiency of a cylinder are the specific inertial parameter K and the ϕ parameter value of interest. The computer output provides the impaction efficiency and an incremental listing of the particle coordinates, velocity components, drag function, and angle of impingement for the final impacting trajectory. Each computation requires approximately 5.6 seconds on a Univac 1108 class computer.

The general method of computation is as follows: A first estimate of the initial y-coordinate trajectory starting position, y_0 , is obtained by the computer based on the input K and ϕ parameter values. The initial starting condition formulas (appendix B) are then applied to generate the particle velocity components and y coordinate at a preselected x coordinate ($x = -5$) in front of the cylinder. The exponential integral is evaluated by the approximation given by Hastings.* The system of equations described by equations 6 through 12 is then integrated by use of the Gill variation of the Runge-Kutta fourth order integration method described by Romanelli.** The y_0 initial starting position is subsequently corrected and updated and the computational process is repeated until a y_0 is found such that its corresponding trajectory path intersects the normalized cylinder radius within a selected degree of accuracy ($0.999999 < R < 1.000001$). The final impacting trajectory is developed and printed out as a function of the time coordinate, τ .

Variations to the program include use of an expanded time scale to achieve finer resolution of the maximum angle of impingement. Decreasing the integration increment, $\Delta\tau$, by an order of magnitude results in an insignificant change of the calculated impaction efficiency.

*Hastings, C. Approximations for Digital Computers. p 190. Princeton University Press, Princeton, New Jersey. 1955.

**Ralston, A., and Wilf, H. S. Mathematical Methods for Digital Computers. John Wiley & Sons, Inc., New York, New York. 1960.

APPENDIX B

INITIAL TRAJECTORY STARTING CONDITIONS FOR LARGE VALUES OF -x

The initial conditions used to start the particle trajectory calculations at a finite distance ahead of the cylinder are based on the analysis given by Langmuir and Blodgett as modified by Torgeson. Initial starting conditions are necessary because it is impractical to integrate the equations of particle motion beginning at $x = -\infty$ and $y = y_0$.

Stokes' law for particle drag is assumed to hold for the particles at great distances ahead of the cylinder. Thus, $C_D Re/24 = 1$ so that the particle equations of motion (equations 6a and 6b) can be written as

$$\frac{dv_x}{d\tau} = \frac{1}{K}(u_x - v_x) \quad (B1)$$

$$\frac{dv_y}{d\tau} = \frac{1}{K}(u_y - v_y) \quad (B2)$$

The time derivative can be eliminated by making x the independent variable,

$$\frac{d}{d\tau} = v_x \frac{d}{dx}$$

Further, since the particle velocity is very nearly equal to the mean airstream velocity at great distances in front of the cylinder, let $v_x = 1 - \epsilon$ where $\epsilon \ll 1$.

The equations of motion can then be written as

$$\frac{d\epsilon}{dx} + \frac{\epsilon}{K} = \frac{1}{K}(1 - u_x) \quad (B3)$$

$$\frac{dv_y}{dx} + \frac{v_y}{K} = \frac{u_y}{K} \quad (B4)$$

where the small terms $\epsilon \frac{d\epsilon}{dx}$ and $\epsilon \frac{dv_y}{dx}$ have been neglected.

The velocity components for the potential flow field can be expressed as series expansions in the form

$$u_x = 1 - \frac{1}{x^2} + \frac{3y^2}{x^4} - \dots \quad (B5)$$

$$u_y = -\frac{2y}{x^3} + \frac{4y^3}{x^5} - \dots \quad (B6)$$

Substituting (B5) into (B3) and assuming that the y displacement (Δy) along the trajectory is so small that y can be replaced by y_0 , a solution is written as

$$\epsilon(x, y_0) = \frac{1}{K} \exp\left(-\frac{x}{K}\right) \int_{-\infty}^x \left[\frac{1}{x^2} - \frac{3y_0^2}{x^4} + \dots \right] \exp\left(\frac{x}{K}\right) dx \quad (B7)$$

The first term of the integral expression of (B7) can be integrated to yield

$$\epsilon_1(x, y_0) = \frac{1}{x^2} \left[\beta + \beta^2 e^{\beta} \text{Ei}(-\beta) \right] = \frac{M(\beta)}{x^2} \quad (B8)$$

where

$$\beta = -\frac{x}{K}$$

$\text{Ei}(-\beta)$ = the exponential integral

x is always a negative distance in the trajectory calculations so that β is always a positive number. The second term of the integral can be solved through integration by parts which yields

$$\epsilon_2(x, y_0) = \frac{y_0^2}{2K^2 x^2} \left[1 - M(\beta) - \frac{2}{\beta} \right] \quad (B9)$$

Therefore, an approximate expression for v_x in terms of the new variable β can be written as

$$v_x(x, y_0) = 1 - \frac{M(\beta)}{x^2} - \frac{y_0^2}{2K^2 x^2} \left[1 - M(\beta) - \frac{2}{\beta} \right] + \dots \quad (B10)$$

The first two terms of this expression are identical to the corresponding terms given by Langmuir and Blodgett.

Returning to (B4) and substituting (B6), a solution for v_y can be obtained after assuming that the Δy displacement is small

$$v_y(x, y_0) = -\frac{1}{K} \exp\left(-\frac{x}{K}\right) \int_{-\infty}^x \left(\frac{2y_0}{x^3} - \frac{4y_0^3}{x^5} + \dots \right) \exp\left(\frac{x}{K}\right) dx \quad (B11)$$

The first term of the integral can be evaluated as before and yields

$$I_1(x, y_0) = \frac{y_0}{Kx^2} \left[1 - M(\beta) \right] \quad (B12)$$

Evaluation of the second term is again accomplished through integration by parts and the equation is written as

$$I_2(x, y_0) = -\frac{y_0^3}{6K^3 x^2} \left(1 - M(\beta) + \frac{6}{\beta^2} - \frac{2}{\beta} \right) \quad (B13)$$

Equation B13 is a corrected form of the Torgeson expression.

The following approximation for v_y therefore results

$$v_y(x, y_0) = \frac{y_0}{Kx^2} \left[1 - M(\beta) \right] - \frac{y_0^3}{6K^3 x^2} \left[1 - M(\beta) + \frac{6}{\beta^2} - \frac{2}{\beta} \right] + \dots \quad (B14)$$

The y-displacement is determined from the equation

$$y - y_0 = \Delta y = \int_{-\infty}^x v_y(x, y_0) dx \quad (B15)$$

After expansion of the exponential integral function, an approximation for Δy is obtained in the form

$$\Delta y = \frac{y_0 M(\beta)}{x^2} + \frac{y_0^2}{6K^2 x^2} \left[1 - M(\beta) - \frac{2}{\beta} \right] \quad (B16)$$

The first terms on the right side of equations B14 and B16 are identical to the Langmuir and Blodgett expressions.

The corresponding expressions for the starting conditions of particle trajectory calculations as given by Langmuir and Blodgett* are:

$$v_x = 1 - \frac{M(\beta)}{x^2} \quad (B17)$$

$$v_y = \frac{y_0 [1 - M(\beta)]}{Kx^2} + \frac{2y_0}{x^5} (1 - 2y_0^2) \quad (B18)$$

$$\Delta y = \frac{y_0 M(\beta)}{x^2} + \frac{y_0 (1 - y_0^2)}{x^4} \quad (B19)$$

$$\beta = \frac{x}{K}$$

* Langmuir, I., and Blodgett, K. B. Army Air Forces Air Materiel Command, Technical Report 5418. A Mathematical Investigation of Water Droplet Trajectories. Contract W-33-038-ac-9151. General Electric Company February 19, 1946. UNCLASSIFIED Report.

Brun and associates state that the Langmuir and Blodgett method of linearizing the equations of motion at large distances ahead of the cylinder has been used in their study. However, the following mathematical expressions for v_y and Δy from their report* differ considerably from those of Langmuir and Blodgett and of this report:

$$v_x = 1 - \frac{M(\beta)}{x^2} \quad (B20)$$

$$v_y = \frac{1 - M(\beta)y_0}{Kx^2} - \frac{2y_0}{x^5} (1 - 2y_0)^2 \quad (B21)$$

$$\Delta y = \frac{y_0 M(\beta)}{x^2} + \frac{y_0(1 - y_0)^2}{x^4} \quad (B22)$$

$$\beta = -\frac{x}{K}$$

The impaction efficiencies determined by Brun *et al.* differ from the efficiencies computed by Langmuir and Blodgett and by this investigator for $K > 1.0$. These differences have been noted in table IV.

* Brun, R. J., Lewis, W., Perkins, P. J., and Serafini, J. S. Impingement of Cloud Droplets on a Cylinder and Procedure for Measuring Liquid-Water Content and Droplet Sizes in Supercooled Clouds by Rotating Multicylinder Method. National Advisory Committee for Aeronautics Report 1215. 1955.

APPENDIX C

IMPACTION EFFICIENCY DATA, FUCHS' DRAG COEFFICIENT

(Starting condition, $X = -5$)

ϕ Parameter	Inertial parameter K	Impaction efficiency E	Maximum $C_D Re/24$ in trajectory
0	0.14	0.00008	1.000 (by definition) ↓
	0.15	0.00057	
	0.16	0.00178	
	0.17	0.00375	
	0.175	0.00497	
	0.20	0.01360	
	0.22	0.02308	
	0.23	0.02782	
	0.25	0.03888	
	0.30	0.06931	
	0.35	0.10011	
	0.40	0.13004	
	0.45	0.15830	
	0.50	0.18574	
	0.54	0.20665	
	0.60	0.23485	
	0.70	0.27874	
	0.80	0.31786	
	0.90	0.35199	
	1.0	0.38229	
	2.0	0.57643	
	4.0	0.73437	
	8.0	0.84529	
	16.0	0.91476	
	32.0	0.95480	
	40.0	0.96336	
	64.0	0.97661	
1.0	0.14	0.00008	1.013
	0.15	0.00056	1.020
	0.16	0.00173	1.021
	0.17	0.00365	1.022
	0.175	0.00481	1.023
	0.20	0.01325	1.026
	0.25	0.03769	1.031
	0.30	0.06698	1.035
	0.35	0.09685	1.041
	0.45	0.15337	1.051
	0.60	0.22794	1.065
	0.80	0.30903	1.079
	1.0	0.37197	1.093
	2.0	0.56356	1.144
	4.0	0.72096	1.210
	8.0	0.83353	1.295
	16.0	0.90550	1.400
	32.0	0.94802	1.526
	64.0	0.97188	1.682

ϕ Parameter	Inertial parameter K	Impaction efficiency E	Maximum $C_D Re/24$ in trajectory
10	0.14	0.00007	1.034
	0.15	0.00052	1.050
	0.16	0.00159	1.053
	0.17	0.00335	1.056
	0.175	0.00453	1.058
	0.20	0.01253	1.066
	0.25	0.03566	1.082
	0.30	0.06332	1.099
	0.35	0.09186	1.115
	0.45	0.14603	1.145
	0.60	0.21685	1.183
	0.80	0.29414	1.223
	1.0	0.35425	1.256
	2.0	0.54115	1.379
	4.0	0.69805	1.531
	8.0	0.81412	1.708
	16.0	0.89100	1.971
	32.0	0.93798	2.192
	64.0	0.96525	2.480
50	0.14	0.00006	1.059
	0.15	0.00048	1.103
	0.16	0.00147	1.110
	0.17	0.00309	1.116
	0.175	0.00416	1.120
	0.20	0.01147	1.136
	0.25	0.03299	1.168
	0.30	0.05767	1.197
	0.35	0.08376	1.227
	0.45	0.13403	1.280
	0.60	0.19971	1.350
	0.80	0.27196	1.421
	1.0	0.32874	1.480
	2.0	0.50969	1.677
	4.0	0.66701	1.922
	8.0	0.78846	2.229
	16.0	0.87213	2.550
	32.0	0.92518	2.961
	64.0	0.95698	3.449

ϕ Parameter	Inertial parameter K	Impaction efficiency E	Maximum $C_D Re/24$ in trajectory
100	0.14	0.00006	1.081
	0.15	0.00045	1.140
	0.16	0.00139	1.149
	0.17	0.00293	1.156
	0.175	0.00393	1.163
	0.20	0.01083	1.183
	0.22	0.01815	1.198
	0.23	0.02226	1.205
	0.25	0.03094	1.222
	0.30	0.05408	1.260
	0.35	0.07818	1.298
	0.40	0.10263	1.334
	0.45	0.12625	1.367
	0.50	0.14752	1.397
	0.54	0.16469	1.419
	0.60	0.18910	1.450
	0.70	0.22429	1.498
	0.80	0.25832	1.539
	0.90	0.28759	1.577
	1.0	0.31343	1.612
	2.0	0.49110	1.846
	4.0	0.64861	2.163
	8.0	0.77310	2.505
	16.0	0.86096	2.932
	32.0	0.91758	3.425
	40.0	0.93068	3.613
	64.0	0.95205	4.048
467	0.15	0.00036	1.261
	0.175	0.00319	1.298
	0.20	0.00882	1.334
	0.25	0.02487	1.399
	0.30	0.04390	1.458
	0.35	0.06420	1.515
	0.45	0.10270	1.620
	0.60	0.15735	1.743

ϕ Parameter	Inertial parameter K	Impaction efficiency E	Maximum $C_{DRe}/24$ in trajectory
500	0.14	0.00005	1.147
	0.15	0.00036	1.268
	0.16	0.00111	1.283
	0.17	0.00233	1.299
	0.175	0.00316	1.306
	0.20	0.00872	1.342
	0.25	0.02457	1.409
	0.30	0.04335	1.468
	0.35	0.06341	1.526
	0.45	0.10165	1.633
	0.60	0.15568	1.760
	1.0	0.26821	2.028
	2.0	0.43552	2.421
	4.0	0.59569	2.881
	8.0	0.72864	3.438
	16.0	0.82653	4.149
	32.0	0.89304	5.019
	64.0	0.93574	6.119
1000	0.14	0.00004	1.169
	0.15	0.00032	1.348
	0.16	0.00097	1.367
	0.17	0.00207	1.385
	0.175	0.00277	1.394
	0.20	0.00746	1.437
	0.22	0.01246	1.470
	0.23	0.01516	1.486
	0.25	0.02105	1.516
	0.30	0.03735	1.589
	0.35	0.05475	1.657
	0.40	0.07212	1.716
	0.45	0.09019	1.777
	0.50	0.10660	1.831
	0.54	0.12040	1.873
	0.60	0.13828	1.937
	0.70	0.16909	2.035
	0.80	0.19511	2.112
	0.90	0.22163	2.199
	1.0	0.24511	2.257
	2.0	0.40644	2.718
	4.0	0.56701	3.280
	8.0	0.70404	3.995
	16.0	0.80766	4.891
	32.0	0.87881	6.021
	40.0	0.89604	6.449
	64.0	0.92570	7.461

ϕ Parameter	Inertial parameter K	Impaction efficiency E	Maximum $C_D Re/24$ in trajectory
10,000	0.14	0.00002	1.260
	0.15	0.00015	1.725
	0.16	0.00047	1.762
	0.17	0.00098	1.797
	0.175	0.00128	1.812
	0.20	0.00346	1.884
	0.22	0.00583	1.945
	0.23	0.00708	1.976
	0.25	0.00995	2.033
	0.30	0.01842	2.156
	0.35	0.02794	2.267
	0.40	0.03797	2.379
	0.45	0.04884	2.468
	0.50	0.05991	2.558
	0.54	0.06796	2.629
	0.60	0.08105	2.737
	0.70	0.10106	2.907
	0.80	0.12059	3.051
	0.90	0.13928	3.197
	1.0	0.15777	3.314
	2.0	0.29402	4.281
	4.0	0.44591	5.451
	8.0	0.59085	6.980
	16.0	0.71334	9.060
	32.0	0.80726	11.815
	40.0	0.83134	12.873
	64.0	0.87327	15.525
19	0.164	0.00217	1.072
19	1.03	0.35341	1.339
19	4.11	0.69281	1.676
39	0.329	0.07424	1.193
39	2.06	0.52291	1.633
39	8.22	0.79720	2.138
65	0.548	0.17465	1.362
65	3.43	0.62819	1.942
65	13.70	0.85207	2.594
77	0.257	0.03505	1.204
77	1.03	0.32680	1.567
155	0.129	(0)	1.033
155	0.514	0.14667	1.472
155	2.05	0.48376	1.997
194	0.412	0.10060	1.433
258	0.137	0.00002	1.051
258	0.856	0.25168	1.763
258	3.42	0.58563	2.449
310	0.257	0.02924	1.352
310	1.03	0.28975	1.890
339	0.235	0.02055	1.338
387	0.206	0.01079	1.319
387	0.823	0.23091	1.845
516	0.428	0.09349	1.617
516	1.72	0.39837	2.334
645	0.343	0.05750	1.563
645	1.37	0.33457	2.282
677	0.470	0.10332	1.711
1129	0.196	0.00642	1.448
1129	0.784	0.18773	2.142

MAXIMUM ANGLE OF IMPINGEMENT, θ_M (RADIAN)

ϕ	K	θ_M
0	0.14	0.0012
	0.15	0.0324
	0.175	0.1046
	0.20	0.1785
	0.25	0.3127
	0.50	0.6905
	1.0	0.9869
	2.0	1.2137
	4.0	1.3582
	16.0	1.5058
	40.0	1.5467
	64.0	1.5485
100	0.14	0.0100
	0.15	0.0296
	0.175	0.0945
	0.20	0.1601
	0.25	0.2762
	0.50	0.6052
	1.0	0.8775
	2.0	1.0880
	4.0	1.2534
	16.0	1.4534
	40.0	1.5107
	64.0	1.5243
1000	0.14	0.0081
	0.15	0.0247
	0.175	0.0788
	0.20	0.1326
	0.25	0.2264
	0.50	0.5033
	1.0	0.7624
	2.0	0.9790
	4.0	1.1536
	16.0	1.3902
	40.0	1.4705
	64.0	1.4978
10,000	0.14	0.0062
	0.15	0.0176
	0.175	0.0548
	0.20	0.0923
	0.25	0.1548
	0.50	0.3784
	1.0	0.6027
	2.0	0.8179
	4.0	1.0104
	16.0	1.2850
	40.0	1.3956
	64.0	1.4420

APPENDIX D

IMPACTION EFFICIENCY DATA, LANGMUIR AND BLODGETT CONDITIONS

ϕ Parameter	Inertial parameter K	Impaction efficiency E
0	0.175	0.005
	0.20	0.014
	0.25	0.039
	0.30	0.069
	0.45	0.158
	0.50	0.185
	0.60	0.235
	1.0	0.382
	2.0	0.576
	4.0	0.733
	8.0	0.844
	16.0	0.912
100	0.175	0.004
	0.20	0.010
	0.25	0.028
	0.30	0.050
	0.45	0.116
	0.50	0.138
	0.60	0.178
	1.0	0.303
	2.0	0.485
	4.0	0.645
	8.0	0.771
	16.0	0.859
1000	32.0	0.915
	40.0	0.928
	0.175	0.002
	0.20	0.006
	0.25	0.017
	0.30	0.032
	0.45	0.084
	0.50	0.101
	0.60	0.134
	1.0	0.243
	2.0	0.405
	4.0	0.565
	8.0	0.702
10,000	16.0	0.806
	32.0	0.877
	40.0	0.894
	64.0	0.924
	0.175	0.001
	0.20	0.002
	0.25	0.008
	0.30	0.017
	0.45	0.049
	0.50	0.061
	0.60	0.081
	1.0	0.157
	2.0	0.292
	4.0	0.444
	8.0	0.509
	16.0	0.715
	32.0	0.809
	40.0	0.833
	64.0	0.874

APPENDIX E

IMPACTION EFFICIENCY FOR INITIAL STARTING

Conditions of $X = -3, -5, -10$ (Fuchs' Drag Coefficients)

ϕ	K	Efficiency values		
		X = -3	X = -5	X = -10
0	0.175	0.005	0.005	0.005
	0.25	0.039	0.039	0.039
	0.50	0.188	0.186	0.186
	1.0	0.385	0.382	0.381
	4.0	0.736	0.734	0.734
	16.0	0.915	0.915	0.914
	32.0	0.955	0.955	0.955
100	0.175	0.004	0.004	0.004
	0.25	0.031	0.031	0.031
	0.50	0.149	0.147	0.147
	1.0	0.316	0.313	0.313
	4.0	0.654	0.649	0.649
	16.0	0.864	0.861	0.861
	32.0	0.920	0.918	0.917
1000	0.175	0.003	0.003	0.003
	0.25	0.021	0.021	0.021
	0.50	0.108	0.107	0.107
	1.0	0.247	0.245	0.244
	4.0	0.572	0.567	0.566
	16.0	0.814	0.808	0.806
	32.0	0.885	0.879	0.878
10,000	0.175	0.002	0.001	-
	0.25	0.011	0.010	0.010
	0.50	0.061	0.060	0.060
	1.0	0.160	0.158	0.157
	4.0	0.452	0.446	0.444
	16.0	0.723	0.713	0.711
	32.0	0.815	0.807	0.804

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13. ABSTRACT The theory of inertial impaction of particles on cylinders has been extended to include small inertial parameter values of interest in chemical operations. Digital computer techniques have been applied to accurately calculate particle trajectories and impaction efficiencies of small particles (10 to 100 μ m in diameter) on man-sized collectors. The results are generalized in graphic form of impaction efficiency versus the inertial parameter. These data are compared with results of previous investigators, namely, Langmuir and Blodgett, and Brun, Lewis, Perkins, and Serafini. Significant differences in impaction efficiency are noted for small inertial parameter values. The data agree within 1% for inertial parameter values exceeding one. Theoretical data indicate that the Stokes' law region for defining the drag force on a particle can be exceeded at some point in the trajectory path for all circumstances of interest in chemical operations.			
14. KEYWORDS			
Droplet	Collectors	Inertial impaction	
Aerosols	Deposition	Inertial parameter	
Particles	Turbulence	Sampling efficiency	
Impaction	Wind tunnel	Collection efficiency	
Efficiency	Impingement	Impaction efficiency	
Sampling	Interception	Isokinetic sampling	
Cylinders	Particle impaction	Deposition efficiency	

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